LLNL-TR-660139

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Research Performance Progress Report

H. Park

September 10, 2014

Disclaimer

This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor Lawrence Livermore National Security, LLC, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Research Performance Progress Report

High Energy Density Laboratory Plasmas
Office of Science, Fusion Energy Sciences

Federal grant: SCW1289
Project/Grant Period: June 2012 – June 2014
Project Title: Measuring Magnetic Fields in Collisionless Shock Experiments on NIF
Principal Investigator
Hye-Sook Park
Physicist
Lawrence Livermore National Laboratory
7000 East Avenue, L-481
Livermore, CA 94500
Telephone: 925-422-7062
Fax: 925-423-6319
E-mail: park1@llnl.gov

Recipient Organization

Lawrence Livermore National Laboratory
7000 East Avenue
Livermore, CA 94550

Reporting Date: Sep. 5, 2014

1. Goals of this project

The major goals of this project is to develop a suite of diagnostics to probe magnetic fields generated by the dynamics of high velocity interpenetrating plasma flows relevant to astrophysical collisionless shocks. Collisionless shocks are common in the universe and are responsible for decelerating and thermalizing supersonic plasma flows and accelerating a fraction of the incident particles to high energies. When high velocity, low density, plasma flows interact in astrophysics, turbulent electrostatic and electromagnetic waves are generated due to plasma instabilities, such as the Weibel instability. This can lead to localized pockets of very strong magnetic field generation. The net result is that the plasmas stagnate in what is called a collisionless shock. Understanding these enigmatic interactions requires well-controlled laboratory experiments able to validate the theory and the simulations. Time and spatially resolved magnetic field diagnostics are key to probing these frontier plasma dynamics, relevant to both astrophysics and laboratory applications of plasma physics. This project will enable us to develop the necessary diagnostics for this experiment on NIF. Our team has vast experience in performing laser experiments, theory, simulations and diagnostic development and is ideally suited for carrying out this work.

2. Accomplishments

Under these goals, in last 3 years, we have studied various options on how to measure the magnetic fields in a laser experiments. Our co-PI (Prof. Radu Presura) at University of Nevada, Reno, concentrated on developing new techniques using Zeeman broadening and Langmuir probes, while the LLNL team performed laser experiments to study the Weibel instabilities generated from interpenetrating high velocity flows. They were designed to investigate high Mach-number non-relativistic collisionless shock formations. The experiments also collected data for the study of self-generated magnetic fields from the Weibel instability in counter-streaming plasma flows, and magnetic field generation and amplification in turbulent flows. The main diagnostics for these experiments were proton probes generated either by the short-pulse laser or the implosion of DHe3 capsules. Many experiments were performed on Omega, Omega EP, Titan, and most recently, we performed one shot on NIF. These experiments produced very meaningful scientific results.

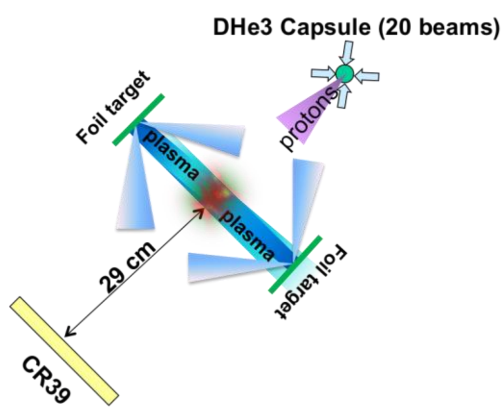

Fig 1. Omega experimental configuration of counter-streaming plasmas. The interaction region is probed by the protons generated by a D^3He imploding capsules

Omega experimental results: We have made considerable progress in previous year's experiments, including the discovery of remarkable, unexpected large, stable, reproducible, self-organizing electromagnetic field structures [N. L. Kugland et al., Nature Physics, **8**, 809, 2012]. These have been seen on OMEGA and OMEGA EP and have been explained as the recompression of magnetic fields generated by the Biermann battery mechanism [D. D. Ryutov et al., Phys. Plasmas, **20**, 032703, 2013; N. L. Kugland et al., Phys. Plasmas,

20, 056313, 2013]. Additionally, these experiments have conclusively measured the plasma flow state in the Omega-60 experiments. These measurements show significant heating of the interpenetrating flows (T_e~1000 eV and T_i~1000 eV) in the double flow geometry due to electron-ion collisions and electrostatic turbulence [J. S. Ross et al., Phys. Plasmas, **19**, 056501, 2012; J. S. Ross et al., PRL, **110**, 145005, 2013; D. D. Ryutov et al., Phys. Plasmas, **18**, 104504, 2011]. The unique diagnostic capabilities, particularly Thomson Scattering on Omega and proton probes on EP, have enabled us to understand the conditions of these flows and to see the surprising electromagnetic field structures.

Recently, double flow experiments on the Omega laser recorded a clear signature of filaments using a D^3He imploding capsule as a mono-energetic proton source. The experimental set-up was similar to our previous experiments: 2 plastic foils separated by 8 mm and each irradiated by ~3.5 kJ of laser energy (Fig. 1). When the plasma flows interact (~4 ns), a D^3He capsule is imploded to generate a point source of protons at 14.7 MeV and 3 MeV. After being deflected by the electromagnetic fields in the flow interaction region, the protons are registered onto a CR39 detector.

The result was quite spectacular, as shown in Fig 2. The left panel is the single flow case and the right panel is the double flow case, where filamentary features are clearly visible along with the co-planar structures. This data motivated a dedicated effort to determine whether these filaments could be generated by Weibel instabilities.

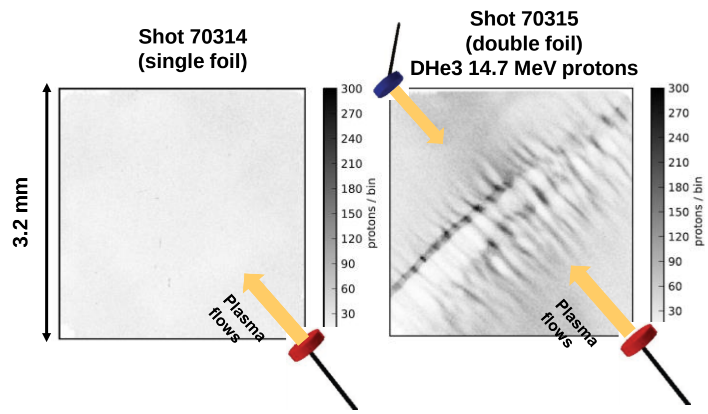

Fig 2. 14.7 MeV proton radiography of high-velocity single and counter-streaming experiments. The filamentary structures in the double flow case are likely generated by the Weibel instabilities.

To understand both the Weibel and Biermann battery generated magnetic fields in our proton imaging experimental system, we have conducted detailed 3-dimensional particle-in-cell (3D PIC) simulations with OSIRIS, where plasma parameters and magnetic fields are shown. The plasma input is from our experimental measurements: $n_e=5\times10^{18}$ cm^{-3}, $v_e=v_i=1000$ km/s, $T_e=T_i=100$ eV. In addition to the filamentary structure, the Biermann battery field that was described in Ref [N. L. Kugland et al., Phys. Plasmas, **20**, 056313, 2013] is also included in the calculation. In order to compare the simulation results with the data, we perform proton ray tracing through the electromagnetic field provided from the 3D simulation. The simulated radiography results are shown in Fig 3, and bear a remarkable resemblance to the data. From these studies of simulation and data, we derive the magnetization, defined as $\sigma = \frac{B^2}{4\pi\rho v^2}$, which quantifies the conversion of kinetic energy to magnetic energy in the system. Figure 6 shows this magnetization as a function of time. Note that the final total magnetization is 0.01, and the initial Biermann battery field plays little role in the magnetization growth. The Weibel instability filamentation is clearly observed in the laboratory and a significant self-generated magnetization is indicated [C. M. Huntington, et al., arXiv:1310.3337, in preparation for Nature Physics submission, 2014].

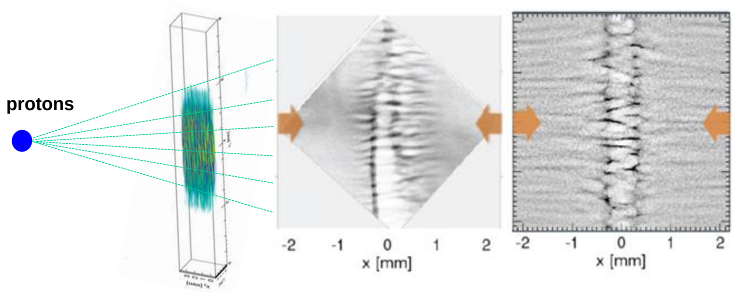

Fig. 3. Schematic of proton image of DHe3 imploding capsule. (a) is the experimental data where the Weibel filamentary structures are clearly observed; (b) is the 3D PIC simulation and the proton ray trajectory from experimental angle. The simulation also added a Biermann battery field that shows as the band structure in the middle.

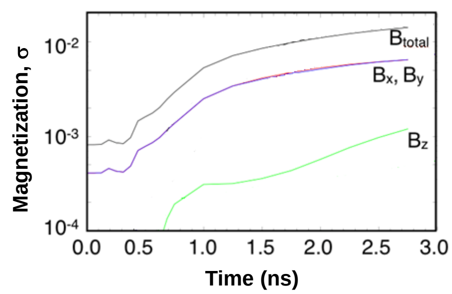

Fig. 4. Magnetization level derived from the 3D PIC simulation after matching the conditions of the Omega data results as shown in Figure 5. The magnetization is achieved up to 1% level.

NIF Experiment: On July 29, 2014, we conducted the first colllisionless shock experiment on NIF. The experiment was carried out by an international team of physicists from Osaka University, Oxford University, Princeton University, MIT, Rochester University, University of Michigan and University of Chicago.

We used 60 NIF beams to deliver 307 kJ of 3ω light to the targets in a 64.5 TW peak power pulse. The experimental configuration is shown in Fig 5. The two resulting plasmas interacted at high velocity in a collisionless shock.

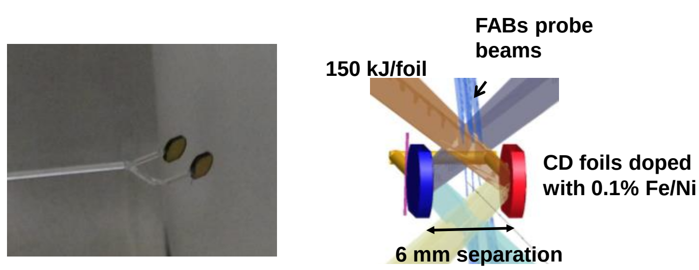

Fig 5. A photo of the NIF target and the experimental configuration for a NIF shot on July 29, 2014.

Neutron-yield diagnostics and x-ray spectral and imaging diagnostics were tested to evaluate the interaction region of the two interpenetrating plasma discs. Stimulated Raman scattering was measured from four laser probe beams.

The experiment yielded excellent results. We observed a high number of neutrons and observed that neutrons came at a relatively late time, which may indicate that they were produced in the shock. We also observed strong x-ray brightening from the hot plasmas in the center of the experiment that had never been seen previously (Fig 6). The backscatter measurements delivered good results as well. With the neutron yield, the delayed neutron production and the x-ray brightening, we are studying whether these signals could be consistent with coming from the shock. However, the team needs to confirm these results with physics 'controlled

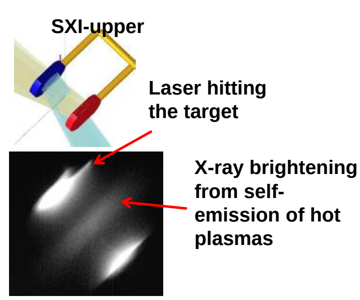

Fig 6. NIF soft x-ray image (SXI) observed x-ray brightening from self-emission.

reference' shots with a single discs and non-deuterated discs. These shots are planned for this fall in 2014. Self-generated magnetic field measurements from the collisionless shock will be done when the proton backlighter capability is available on NIF next year.

3. Products

Publications: This project and collaboration produced numerous publications including 2 Nature Physics articles, a PRL and one in preparation for submission to Nature Physics..

1. C. Huntington," Observation of magnetic field generation via the Weibel instability in interpenetrating plasma flows", Nature Physics, in preparation (2014).
2. J. Meinecke et al.,"Turbulent amplification of magnetic fields in laboratory laser-produced shock waves", Nat. Phys. 10, 520 (2014).
3. J.S. Ross, J.D. Moody, F. Fiuza, D. Ryutov, L. Divol, C.M. Huntington. "Thomson scattering measurements from asymmetric interpenetrating plasma flows." Rev. Sci. Instrum. 85, 11E613, (2014).
4. D. D. Ryutov, F. Fiuza, C.M. Huntington, J.S. Ross, H.-S. Park. "Collisional effects in the ion Weibel instability for two counter-propagating plasma streams." Phys. Plasmas, 21, 032701 (2014).
5. M. J. Grosskopf et al., "Simulation of laser-driven, ablated plasma flows in collisionless shock experiments on Omega and the NIF", HEDP, 9, 192-197, 2013
6. N. L. Kugland et al., "Visualizing electromagnetic fields in laser-produced counter-streaming plasma experiments for collisionless shock laboratory astrophysics", Phys. Plasmas, 20, 056313 (2013)
7. J. S. Ross et al, "Collisionless coupling of ion and electron temperatures in counter-streaming plasma flows", PRL, 110, 145005 (2013)
8. D. D. Ryutov, et al., "Magnetic field advection in two interpenetrating plasma streams", Phys. Plasmas, 20, 032703 (2013)
9. Y. Sakawa et al., "High-power laser experiments to study collisionless shock generation", EPJ Web of Conferences, 59, 15001 (2013).
10. M. Fatenejad et al., "Modeling HEDLA magnetic field generation experiments on laser facilities", High Energy Density Phys. 9, 172 (2013).
11. N. L. Kugland et al., "Self-organized electromagnetic field structures in laser produced counterstreaming plasmas", Nat. Phys., 8, 809-812 (2012).
12. N. L. Kugland, et al., "Relation between electric and magnetic field structures and their proton beam images", Rev. Sci. Instrum., 83, 101301 (2012) (Invited Article).
13. J. S. Ross et al., "Thomson scattering diagnostic for the measurement of ion species fraction", Rev. Sci. Instrum., 83, 10E323 (2012).
14. D.D. Ryutov et al., "Basic scalings for collisionless shock experiments." Plasma Phys. Contr. F., 54, 105021, October (2012).
15. D. D. Ryutov et al., " Intra-jet shocks in two coutner-streaming, weakly, collisional plasma jets", Phys. Plasmas, 19, 074501 (2012).
16. H.-S. Park et al., "Studying astrophysical collisionless shocks with counter-streaming plasmas from high power lasers", High Energ. Dens. Phys., 8, 38-45 (2012).
17. G. Gregori et al., "Generation of scaled protogalactic seed magnetic fields in laser-produced shock waves", Nature, 481, 480-484 (2012).

18. J. S. Ross et al., “Characterizing counter-streaming interpenetrating plasmas relevant to astrophysical collisionless shocks”, Phys. Plasmas, 19, 056501 (2012).

Presentations:

1. H. S. Park,56th APS/DPP, Oct, New Orleans, 2014 (invited)
2. H. S. Park, HEDLA, 2014, France, (contributed)
3. F. Fiuza, HEDLA, 2014, France, (invited)
4. S. Ross, HTPD, 2014, (contributed)
5. F. Fiuza, UCLS Plasma Colloquium, 2014, (invited)
6. F. Fiuza, Astrophysics Seminar at NBIA, Copenhagen, Denmark, 2014, (invited)
7. F. Fiuza, NIF User Group Meeting, 2014, poster, (contributed)
8. G. Gregori, HEDLA, 2014, France, (invited)
9. Y. Sakawa, HEDLA, 2014, France (invited)
10. F. Fiuza, NIF User Group Meeting, 2014, poster, (contributed)
11. H. S. Park, US-Japan Workshop, 2014, Japan (invited)
12. A. Spitkovsky, US-Japan Workshop, 2014, Japan (invited)
13. D. D. Ryutov, Symposium, “Sagdeev at 80”, University of Maryland, February 7-8, 2013; College Park, Maryland,2013, (invited)
14. H. S. Park, IFSA 2013, (invited)
15. A. Arias, et al. 55th APS DPP, Nov. 11-15, 2013, Denver CO (poster)
16. C. Plechaty, et al., 55th APS DPP, Nov. 11-15, 2013, Denver CO (poster)
17. G. Gregori, 40th EPS Conference on Plasma Physics, Espoo, Finland, July 1-5, 2013 (invited)
18. F. Fiuza, APS/DPP, 2013 (contributed)
19. D. D. Ryutov, University of Rochester Colloquium, 2013, (invited)
20. H. S. Park, APS/DPP, Turbulent mixing, 2013 (invited)
21. S. Haque, et al., 55th APS DPP, Nov. 11-15, 2013, Denver CO (poster)
    NIF & JLF User Group Meeting 2014, Feb 9-12, 2014, LLNL (poster)
22. H. S. Park, HEDLA, 2012, Florida (invited)
23. N. Kugland, APS/DPP, 2012 (invited)
24. H. S. Park, IFSA, 2011 (invited)
25. S. Ross, APS/DPP, 2011, (invited)

4. Participants and other collaborating organizations

We had many graduate students and post-docs as well as designers and experimenters. The younger members were:

- Jena Meinecke, graduate student (Oxford University), 0.5 FTE
- Alex Zylstra, graduate student (MIT), funded by SSAA program
- Matthew Levy (Rice University): Lawrence Graduate Scholar
- A. Arias (Univ. of Nevada, Reno): graduate student, 0.5 FTE
- S. Haque (Univ. of Nevada, Reno): graduate student, 0.5 FTE
- Nathan Kugland (LLNL): 0.5 FTE
- Steve Ross (LLNL): 0.5 FTE (converted to FTE after 2 years)
- Channing Huntington (LLNL): 0.5 FTE
- C. Plechaty (LLNL): Post-doc: 0.5 FTE
- Frederico Fiuza (LLNL): Lawrence Fellow Postdoc

- Brad Pollack (LLNL), Lawrence Fellow postdoc
- Hye-Sook Park (LLNL), PI for this program, 0.1 FTE
- Steve Weber (LLNL), Rad-Hydro designer, 0.05 FTE

This project formed an internation collaboration called: Astrophysical Collisionless Shock Experiments with Lasers (ACSEL). The collaborators are from Osaka University, Oxford University, Princeton University, MIT, University of Michigan, University of Rochester, Rice University, University of Chicago, York University, and LULI. The majority of the collaboration members are not supported by this grant.

5. Impact

This project provides a controlled laboratory platform to study the formation and evolution of astrophysically-relevant collisionless shocks created by counter-streaming plasmas. Our results will provide fundamental and quantitative understanding of the basic physics mechanisms by which a high-velocity flow environment contributes to the evolution of astrophysical objects and the generation of high-energy cosmic rays. Both of these phenomena have been unsolved problems in astrophysics for more than half a century.

This project is of great interest to the international laboratory astrophysics community, as can be seen by the enthusiastic participation in our collaboration of scientists from universities and national laboratories worldwide. Moreover, this project has already attracted young scientists to the field. Thanks to this HEDLP program, a number of new young post-doctoral researchers joined the project: Steve Ross was a post-doc for this project and now promoted to be a staff member at LLNL. Channing Huntington is a post-doc at LLNL; Frederico Fiuza and Brad Pollack are Lawrence Fellow Post-doctoral scholars at LLNL. There are many more students and post-docs among our collaborators such as Jaehong Park (Princeton) Damiano Caprioli (Princeton), Jena Meinecke (Oxford), P.-Y. Chang and Dan Barnak (LLE), Chris Murphy (now at Edinburgh), Taichi Morita (Osaka), Peteros Tzeferacos (Chicago) who are actively participating the current Omega, Omega-EP and NIF experiments. These high-power lasers are ideal for this project since they enable a new class of experiments with the larger-scale, higher-velocity, higher-temperature plasma flows that are required to observe the signatures of collisionless shocks.

Diagnosing the magnetic fields in dynamic plasma interactions is important to the many HED, ICF, and fundamental science groups. This project demonstrated the use of a proton source in the HED environment as well as new techniques developed by the University of Nevada, Reno.

6. Change/Problems

Funding for the National Labs from this program no longer continues. This means the delivery to the DOE/Fundamental Science program will be reduced.